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TECHNICAL NOTE No: R.P.D. 19

MIXING NOZZLES FOR LIQUID-FUEL ROCKET MOTORS

By

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Technical Note No. R.P.D.19

August, 1949

ROYAL AIRCRAFT ESTABLISHMENT, FARNBOROUGH

Mixing Nozzles for Liquid-Fuel Rocket Motors

By

and others

J. Diederichsen, H. Walder and H.H. Treutler
Rocket Propulsion Department, Westcott

SUMMARY

When two immiscible liquids are to be used as rocket propellants it may be advantageous to spray them as a fine emulsion into the combustion chamber. Experimental work has been carried out on nozzles in which two liquids are caused to form an emulsion by means of rotational forces resulting from the pressure drop in various swirl nozzles. Modifications of well known types of swirl atomizers have been tried, but the best results have been obtained with a nozzle designed specially for mixing. Proposals are made for determining whether mixing nozzles give results which are better than those obtained by conventional methods of injection.

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1. Liquid rocket propellants
2. Spray nozzles
3. Rocket motor nozzles

I. Diederichsen, J.
II. Title

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1 Introduction

In order to achieve combustion in a smaller space than that required with normal methods of injection, Dr. J. Schmidt proposed that a type of nozzle might be used in which the propellants were mixed to an emulsion just before they were sprayed into the combustion chamber. Some combustion experiments with a conventional type of swirl nozzle were made to try out this proposal, but the results were insufficient to determine the value of mixing nozzles. The tests and calculations described in this note were undertaken to obtain additional information.

Due to the intimate mixture of the propellants, higher rates of combustion may be expected by the use of a mixing nozzle. Mixture, however, must be confined to a small space owing to the danger of explosion in the emulsion. Hitherto good atomization and mixture of propellants in the combustion chamber has had to be effected by a number of small nozzles. With a mixing nozzle of suitable design it should be possible to replace them by a single nozzle. Although the drops may be larger, they should need no further atomization because it is considered that they will detonate on ignition. It is not yet known exactly how single drops of propellant emulsion burn, but this will be investigated when facilities are available.

At the start of these tests, it seemed almost certain that a simple type of nozzle could be used to prepare an emulsion, since according to the conclusion reached by the Joseph Lucas Research Laboratories[1] "The actual atomization at high pressure is primarily due to micro-turbulence resulting from the very high throat velocities."

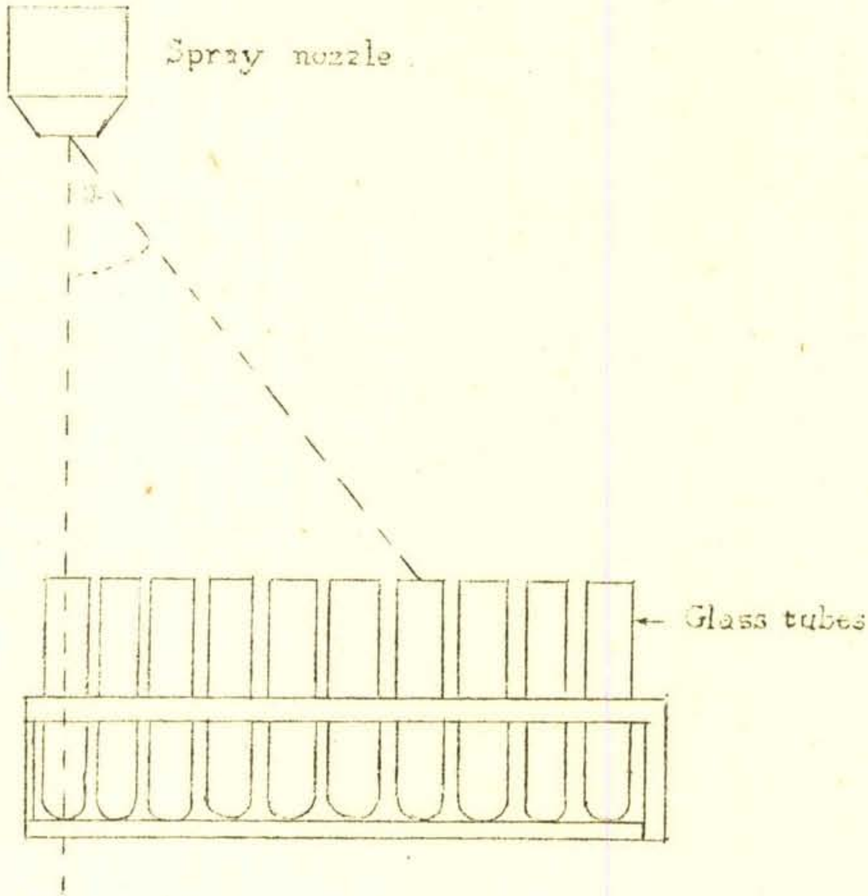
An attempt was made to examine the behaviour of a mixture of propellants in the usual type of swirl nozzle by replacing parts of the steel nozzle by glass, but little could be seen apart from the fact that an emulsion was formed. As the emulsion is turbid the mechanism of formation cannot be studied, and it is still not known how the opposing forces of centrifugal force and friction interact upon the drops of denser and lighter immiscible liquids. Earlier investigations in this subject, however, show what happens when only one liquid passes through the nozzle[1,2].

2 Performance of a simple swirl nozzle used an an emulsifier

2.1 Apparatus

A nozzle from a hydrogen peroxide "steam generator" was used for these tests. This nozzle (see Fig.1) has two tangential inlet holes giving a hollow cone spray with a throughput of 60 gm/sec at a pressure of 7 atm(gauge). The nozzle was connected by two pipes to two containers from which paraffin and water respectively could be fed by compressed air; the rates of flow were controlled by valves situated in the feed pipes. The two liquids have different densities and are of course immiscible. It was found that a coarse mixture was produced where the two liquids met just above the swirl-plate of the nozzle, but a more intimate mixture was produced in the swirl chamber. To sample the mixture distribution across a section of the spray 36 test tubes were placed 14 cm below the nozzle, as shown in the diagram. The method of determining the mixture distribution is described in Appendix I.

/Diagram



2.2 Experimental Results

For the first test the mean ratio of paraffin to water was 1 to 1.4 by volume. The mixture ratio inside and outside the spray cone at each of eight points is shown in fig.2: a shaded field of 1 mm indicates 1% deficiency below the mixture ratio 1/1.4 and an unshaded field of 1 mm 1% excess of water above the mixture ratio 1/1.4. The average deviation was 5.9%. Fig.2 also shows the mass distribution of the spray.

It was found that the above deviation from the mean mixture ratio undergoes no substantial alteration when the surface tension (soap solution with surface tension 31 dynes/cm instead of water with surface tension 72 dynes/cm), or the density ($CaCl_2$ solution with density 1.25 gm/cc instead of water with density 1.0 gm/cc), or the mean mixture ratio (1/3 instead of 1/1.4) is changed. There is every reason, therefore, to suppose that the performance of this nozzle will be the same with paraffin and nitric acid or with paraffin and hydrogen peroxide which is the propellant combination used in combustion tests. On the other hand, this type of mixing nozzle gives no better result than a nozzle delivering two interpenetrating spray cones for fuel and oxidant respectively as the mixture ratio is incorrect, but with interpenetrating sprays the correct mixture ratio is bound to be reached somewhere. This is true, however, only for macroscopic mixing, and the nozzle tested may have the advantage that the paraffin droplets are smaller than they would be if the paraffin were atomized separately. The droplet size can be estimated from the microphotograph (fig.3a) which was obtained from an emulsion stabilized by adding 0.1% soap to the water before the liquids were sprayed through the nozzle. The paraffin droplets show up as white spots. Apart from a few large drops, the droplets are about 0.01 mm or less in diameter, and are smaller than those usually obtained from swirl nozzles. As it was thought possible that the paraffin drops had been further divided on impact with the walls of the glass beaker in which the emulsion was collected, single drops were caught on a glass slide at some distance from the nozzle where their speed was lower. Out of more than 100 drops examined under the microscope, none were found to consist of one liquid, and all were of an emulsion finer than that shown in fig.3a. It is, therefore, concluded that the large drops have been formed by recombination.

Single droplets were not photographed because there is always movement inside them, and only a small part of a globule is sharply defined under the microscope.

The results with this type of mixing nozzle may be summarized as follows:-

The mixture ratio is not uniform across the spray cone, but very fine atomization is obtained. Owing to the unsymmetrical distribution it is unlikely that nozzles of this type will give good results in very small combustion chambers.

2.3 Characteristics of the Emulsion

Paraffin-water emulsions may be either emulsions of paraffin in water or of water in paraffin. The white globules seen in the microphotograph are paraffin droplets; this was established by making an emulsion with coloured paraffin which yielded coloured droplets in colourless water.

Emulsions are strongly influenced by soaps; alkali soaps usually yield paraffin-in-water emulsions. As sodium soap was used as a stabilizer, this suggests that the emulsion might be paraffin in water. When, however, no soap was used a paraffin in water emulsion was obtained which was sufficiently stable to show that it could be readily diluted with water, but not with paraffin; this means that paraffin is the dispersed medium. The microscope also shows that the density of the small paraffin globules is less than that of the surrounding water, as when the microscope objective is raised, the "Beckes line" moves into the globules.

3 Existing Solid Cone Mixing Nozzles

Only one reference to mixing nozzles has been found described in the literature[3]; in this article is described a solid cone nozzle with a separate feed line to the axial jet. A solid cone nozzle is a hollow cone nozzle with the addition of an axial jet which strikes the rotating fluid and breaks it up just within the orifice. Although solid cone nozzles have been known for a long time, this principle has not been used very much for rocket motors.

A solid cone would have the advantage of making better use of the space in the combustion chamber and of providing more uniform distribution of hydrogen peroxide in steam generators. It was thought desirable, therefore, to examine the sprays from solid cone nozzles.

3.1 Experiments with a Solid Cone Nozzle with One Liquid

As in the previous experiments a nozzle from a steam generator was used. An additional hole was drilled through the centre of the swirl plate (see fig.1), and the distance from this plate to the orifice was adjusted so as to produce a uniform mass distribution in the spray cone. It is difficult to make the distribution of the spray of a solid cone uniform, and the effect of slight variations in design are shown in fig. 4-7. To facilitate comparison, the ordinates of the curves and those of 4-11 representing mass flow per unit area have been reduced so that the maxima have a value of unity.

One of the disadvantages of this type of nozzle is that it must be made much more accurately than the usual hollow cone nozzle. Fig.5 and fig.6 show the different forms of spray that were obtained from a similar nozzle by altering the length of the swirl chamber by less than 1% i.e. 0.1 mm; fig.7 shows the spray from another solid cone nozzle in which the axis of the central jet was inclined at about $3\frac{1}{2}^{\circ}$ to the orifice axis. Because of the influence of these small deviations, difficulties would be encountered in manufacturing these nozzles, since each nozzle would have to be inspected, and in many cases readjustment might be necessary. A comparison of the spray from a hollow cone nozzle (fig.8) and that from a solid cone nozzle (fig.4) show that the improvement in mass distribution appears to make it worth while to use the solid cone nozzle for certain applications, such as hydrogen peroxide steam generators, despite the closer manufacturing limits required. It is important, especially in steam generators, that the hydrogen peroxide is distributed evenly on the surface of the catalyst, and the solid cone nozzle should be better than a number of hollow cone nozzles.

A disadvantage of the solid cone nozzle is that the drops produced by it are larger than those from a hollow cone nozzle. To measure the drop size a mechanical shutter device was used to collect a sample of drops (see Appendix II). It was found that the drops from the solid cone nozzle (fig.1b) were bigger than drops from the simple swirl nozzle (fig.1a) without a central jet. The measurement of drop size is described in Appendix II. The relatively large size of the drops is a drawback when the propellants are atomized separately, but it is probably of less importance when the propellants have been mixed to an emulsion before atomization.

Where big drops are a drawback but it is desirable to use a solid cone, a double cone nozzle, which has been proposed by W. Kretschmer, can be used with advantage. This nozzle delivers two hollow spray cones similar to those used for mixing oxidant and fuel inside the combustion chamber, but in this case the apex angle of the inner cone is smaller than that of the outer cone, so that the two concentric cones interfere only slightly with one another. The spray pattern of fig.9 was obtained from a double cone nozzle of this type. The distribution of the spray can be made more uniform if the difference between the apex angles of the cones is reduced, and a still nearer approach to uniformity can be obtained if the inner cone is made solid. This type of nozzle, is similar to a single solid cone nozzle except that the spray round the periphery of the cone, which forms a large part of the total, is finer.

3.2 Experiments with a Solid Cone Nozzle used as a Mixing Nozzle

In order to use the solid cone nozzle as a mixing nozzle it was necessary to modify the apparatus so that the central jet and the tangential holes could be fed from separate containers. A nozzle of this type was made (see fig.12); paraffin was fed through the central jet and water through the outer annulus and the pressure of the central jet was adjusted to give a uniform spray. The mixing effect was fairly good. Fig.10 shows that the central paraffin jet is distributed throughout the cone, but that the mixture ratio paraffin/water decreases from the centre to the periphery. On the whole, therefore, the mixing effect of this nozzle is not as good as that of a swirl nozzle in which both liquids are fed through tangential holes.

As denser liquids tend to reach the outside of the spray cone, mixing might be better if the central jet were water, and paraffin were fed through the tangential holes. This method was tried and, as can be seen from fig. 11, the distribution of each liquid was different from that in the previous test (fig. 10) but the mixing was no better.

4 New Type of Mixing Nozzle

The spray from an ideal mixing nozzle should be a fine emulsion, and the mixture ratio should be the same in all parts of the spray. These two factors are of vital importance, since combustion occurs very near to the orifice of the mixing nozzle. This has proved to be the case with nitric acid and paraffin.

From the foregoing experiments it is clear that it is possible to make emulsions by means of swirl nozzles and when these emulsions are collected in a container they are found to be very finely divided and appear to be homogeneous, though the mixture ratio of the two liquids varies for samples of emulsion taken from different points of the spray cone.

Although tests showed that solid cone nozzles were not as good mixing devices as swirl nozzles it seemed possible that they could be improved by drilling additional holes at an angle to the main axis. This modified nozzle, adjusted to give the correct mixture ratio is the basis of the new type of mixing nozzle described below.

4.1 Experimental Nozzle Design

In order to investigate a wide range of throughputs, two sizes of nozzle were designed. As a basis for experiment the following throughputs were chosen for 10 atm. feed pressure for both liquids.

Nozzle A (medium size) throughput 1000 gm/sec (2.2 lb/sec)
Nozzle B (large size) throughput 5000 gm/sec (11 lb/sec)

Each nozzle was made with three different values of β (the semi included angle) 15°, 30° and 60° respectively for the swirl chamber. The complete nozzle consists of easily interchangeable parts of light alloy. A section of the nozzle is shown in fig. 14 and the photograph, fig. 15, shows the medium size nozzle ($\beta = 15^\circ$) in operation at a pressure of 10 atm (gauge). The tangential inlet holes into the swirl chamber were drilled through a jig in such a way that both liquids are forced to swirl round in the same direction; the water comes from the outside and the paraffin from the middle. In every case the swirl chamber was made of such a length that the outlet orifices were the same size for nozzles of the same size group regardless of the value of β. The feed pressures were measured on large diameter pipes very near to the nozzle. At the highest throughput (5000 gm/sec) the velocity was only 1.9 m/sec in the pipes and so the loss of pressure head was less than 0.02%.

4.2 Experimental Results

Tests were carried out at 5 and 10 atm feed pressures with both sizes of nozzle and the three different swirl chamber angles. The apex angle of the spray cone, 2α, was measured on the photographs taken during the spray tests. In order to examine the performance test tubes were placed under the nozzle which was arranged to spray vertically downwards as shown on page 4. Samples were taken at different points of the spray cone and the ratio of water to paraffin was determined as described in Appendix I. To examine the emulsion another sample was collected in a large beaker from which a sample was taken with a pipette and placed between two slides for examination under the microscope. Microphotographs were taken of the emulsion in some cases, but owing to the lapse of time, which occurs before a photograph can be taken and the consequent recombination of the paraffin droplets, it was found better to judge the quality of the emulsion by observation through a microscope. All the microphotographs were similar to that shown in fig.3a although the emulsion is slightly coarser for a feed pressure of 5 atm than of 10 atm. The only exception was an emulsion obtained from nozzle A with $\beta = 60^{\circ}$; a microphotograph of this emulsion is shown in fig.3b. This emulsion is seen to be coarser than that from other nozzles.

A series of tests were made to determine the mixture ratio distribution for nozzles A and B and the results are summarized in Table I from which it is clear that nozzles with angle $\beta = 30$ are the most suitable for use as mixing nozzles. The detailed results are given in Appendix III.

Table I

Deviation from average mixture ratio of emulsion

Nozzle	Nozzle Angle β	% Deviation from Average Mixture Ratio of Emulsion		Mean Deviation % from Average Mixture Ratio of Emulsion
		(Feed Pressure 5 Kg/sq.cm.)	(Feed Pressure 10 Kg/sq.cm.)	
A	15°	0.4	1.3	0.9
	30°	0.9	0.9	0.9
	60°	0.2	1.7	1.0
B	15°	2.2	3.3	2.7
	30°	1.7	0.2	1.0
	60°	3.4	3.1	3.3

4.3 Calculations on Optimum Mixing Nozzle

Calculations were made by H. H. Treutler of this department to take into account the mechanical variables of the mixing process in order to design the optimum mixing nozzle; the mathematical discussion is included as Appendix IV of this note. For this purpose the centrifugal acceleration a_c of the mixture and the total acceleration a at varying spray cone angles α were calculated for different nozzle angles β. The corresponding centrifugal "velocity" $\int |a_c| dt$ and total "velocity" $\int |a| dt$ were obtained by integration. The values of acceleration and "velocity" as a function of the spray cone angle α are plotted in fig.16 for the three cone angles β. The curves show wide variation in shape so it should be possible to determine experimentally which of the four variables has a decisive effect on mixing. As has already been pointed out, of the nozzles tested those with $\beta = 30^{\circ}$ give the best results, but to obtain a final decision on the effect of the four variables a large number of experiments would be necessary; since effective mixing has already been obtained this programme of work has not been undertaken. If, however, mixing nozzles become standard equipment this work would be of great importance in effecting further improvement to the design.

5 Conclusions

The experiments described in this note show that a fine emulsion of fuel and oxidant can be made in a small space. It is, therefore, considered worthwhile pursuing work on the use of emulsions, and it is proposed that this should be done in two stages. Firstly, the combustion of individual droplets of emulsion should be examined in the laboratory to determine whether their rate of combustion is greater than that of separate droplets of fuel and oxidant. A few experiments have already been made, but the work requires special safety facilities which are not at present available. Secondly the performance of motors with mixing nozzle burners should be compared with motors using separate injection system for the fuel and oxidant in order to determine whether a smaller value of the characteristic length

$$L^* = \frac{\text{combustion chamber volume}}{\text{throat area}}$$

can be obtained by the first type of injection system than by the second.

REFERENCES

No.	Author	Title, etc.
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APPENDIX I

Determination of Mixture Ratio in the Spray

In order to determine the mixture ratio test tubes for taking samples were placed under the nozzle. These tubes had sharp edges, and small measured quantities of hydrochloric acid were filled into them in order to make the emulsion separate quickly and to fill the round bottom of the tube. The heights of the paraffin and water were then measured by means of a rule.

This method was useful for rough estimations, but was not good enough for exact measurement, mainly because the water/paraffin interface in the tube was not clear. For exact measurements samples were taken with the same test tubes clean and dry. Immediately after spraying the samples were poured into pyknometers and then the mixture ratio was determined from the density of the samples. This method proved to be very accurate and the density could be determined at any convenient time, as the total volume of the emulsion does not change when the emulsion is partly or completely separated.

The percentage of water in the emulsion is given by the following expression:

$$\% H_2O = \frac{100\,(d_e - d_p)}{d_{H_2O} - d_p}$$

where d_e is the density of the emulsion
d_p is the density of the paraffin
and d_{H_2O} is the density of the water.

APPENDIX II

Drop Size of Spray from Solid Cone Nozzle

The spray from a solid cone nozzle looks much more coarse than that of a hollow cone nozzle. The Chemical Engineers Handbook[3] says: "The hollow cone nozzle usually yields a somewhat smaller range of drop size than the solid cone nozzle", (no figures are given); this was confirmed by measuring drop sizes from sprays of the simple nozzle with and without central jet (fig. 1b and 1a). From fig. 13 it will be seen that the solid cone spray comprises much larger drops than the hollow cone spray at the same feed pressure. It should, however, be pointed out that no alteration was made on the tangential inlet holes, the throughput was, therefore, higher for the solid cone than for the hollow cone and a higher throughput at the same feed pressure usually produces bigger drops. Nevertheless, it is clear that the size distribution for these two types of nozzles is different.

The above measurement was taken by means of a spray sampling device, consisting mainly of a spring operated shutter, below which a slide of glass coated with vaseline was placed. Immediately after spraying, an enlarged photograph was made from the slide. The diameters obtained from the photograph were multiplied by 0.8 because according to Houghton and Badford[5] the flattening coefficient for water resting on vaseline is 0.8 ± 0.04. The flattening coefficient, which is the ratio between the true diameter of the globule and the observed diameter, depends on the contact angle between the drop and the slide-surface and is independent of the drop size for drops up to about 1 mm in diameter.

APPENDIX III

Mixture Ratio Distribution for Experimental Nozzles

The results of tests on experimental nozzles A and B for two different injection pressures and three different nozzle angles are given in Table II which shows the average percentage of water and the deviation from the average percentage of water at different points of the spray.

Table II

Deviations from average emulsion mixture ratio for experimental nozzles

Nozzle Angle β	Feed Pressure (kg/cm^2)	Nozzle A: Average % of water	Nozzle A: Deviation from Average % of water	Nozzle B: Average % of water	Nozzle B: Deviation from Average
15°	5	80.3	-0.1 +0.1	86.2	-2.9 -1.5
		81.9	+0.3 -1.0 -0.2 +0.9 0 -0.7		+1.7 +2.7
15°	10	80.5	+2.4 +1.0 +1.1 +0.3 -3.2 -1.8 -0.7	85.6	-7.9 -1.5 +0.9 +2.9 +3.2
		80.3	-1.1 +0.7 +0.5		
30°	5	79.4	+1.3 -0.8 -0.6	86.7	+0.9 +0.8 -3.4 +1.7
30°	10	77.6	-0.2 +0.2	86.8	-0.2 +0.1
		81.2	+0.4 +1.9 -0.8 -1.5		
60°	5	73.8	-0.2 +0.2	83.9	-5.7 +2.6 +2.0
60°	10	74.7	+3.5 -1.9 -1.5 -0.1	83.3	-2.8 -1.9 +4.7

For each test the average percentage of water in the spray was taken from all the samples collected during the test. Two figures of the average percentage of water for one nozzle indicate that two tests have been made on the nozzle. In columns 4 and 6 are given for nozzles A and B respectively the deviations from the average percentage of water for each series of tests. When the figures in columns 4 or 6 for one nozzle are separated by a horizontal line this indicates that the samples were taken at points in the spray cone at right angles to one another. In all cases the first figure relates to the inside edge of the cone and the last to the outer edge. Additional figures indicate samples taken at equal intervals across the cone.

Although the mixture ratio distribution for nozzle A ($\beta = 60^o$) is fairly good this nozzle seems to be unsuitable for use as a mixing nozzle because the emulsion is coarse. The other two nozzles of this size ($\beta = 15^o$ and $\beta = 30^o$) show no difference in the quality of the emulsion produced and their mixture ratio distribution characteristics are almost identical. Both nozzles can be considered satisfactory. The maximum deviation from the average mixture ratio was 1.9% for nozzle A ($\beta = 30^o$) and slightly greater than that for nozzle A ($\beta = 15^o$), hence the former may be recommended for further experiments. The Joseph Lucas Research Laboratories have also decided to use simple swirl nozzles with $\beta = 30^o$[4].

For the B series of nozzles with a throughput of 5000 gm/sec (11 lb/sec) that for which $\beta = 60^o$ shows the worst mixture ratio distribution characteristics. The one big deviation of 7.9% for $\beta = 15^o$ is probably an experimental error, as the deviation is otherwise fairly uniform. Hence the B nozzles with $\beta = 15^o$ and $\beta = 30^o$ are about equal and almost as good as the smaller ones. It should also be noted that in no case does the lighter or heavier liquid tend to be inside or outside the spray cone; all deviations from the mean mixture ratio are quite irregular.

APPENDIX IV

Calculations on Optimum Mixing Nozzle

By

H.H. Treutler

1 Introduction

This work was originally undertaken at the suggestion of and in conjunction with the late Dr. J. Schmidt of this Department. It deals with the mixing of liquids by the action of a nozzle and details are given of calculations based on various values of the nozzle angle. The efficacy of the nozzle as a mixing device is assumed to depend on one of four quantities and it is concluded that their order of importance can be determined experimentally.

2 General Considerations

The problem is to force the liquids into one another, in other words, the motion of the liquids relative to each other is to be accelerated. Obviously use will be made of centrifugal acceleration by injecting the liquids tangentially into the nozzle. A linear acceleration moves all particles equally; it might, therefore, be expected that centrifugal acceleration is more important in mixing since it is not constant all over a cross section of a nozzle.

A linear acceleration can, however, only be effected by using a force; in this case the force used is the injection pressure; hence substances differing in density have different linear accelerations. Therefore, the total acceleration is more likely to be a measure of the effectiveness of the mixing. In addition, there is the possibility that the mixing may be improved by allowing the acceleration to act for a longer time; this suggests that the time integral of the acceleration may be the decisive factor. On the other hand, centrifugal acceleration acting for a long period may redissolve different heavy substances.

3 Detailed Analysis

It is clear from the above that four quantities can affect the mixing. These are the centrifugal acceleration, the total acceleration, the time integral of centrifugal acceleration and the time integral of total acceleration. These four quantities will now be discussed mathematically in order to relate them to magnitudes measurable in experiments. The symbols used in the discussion are indicated overleaf, and are also shown in the following diagram.

/Diagram

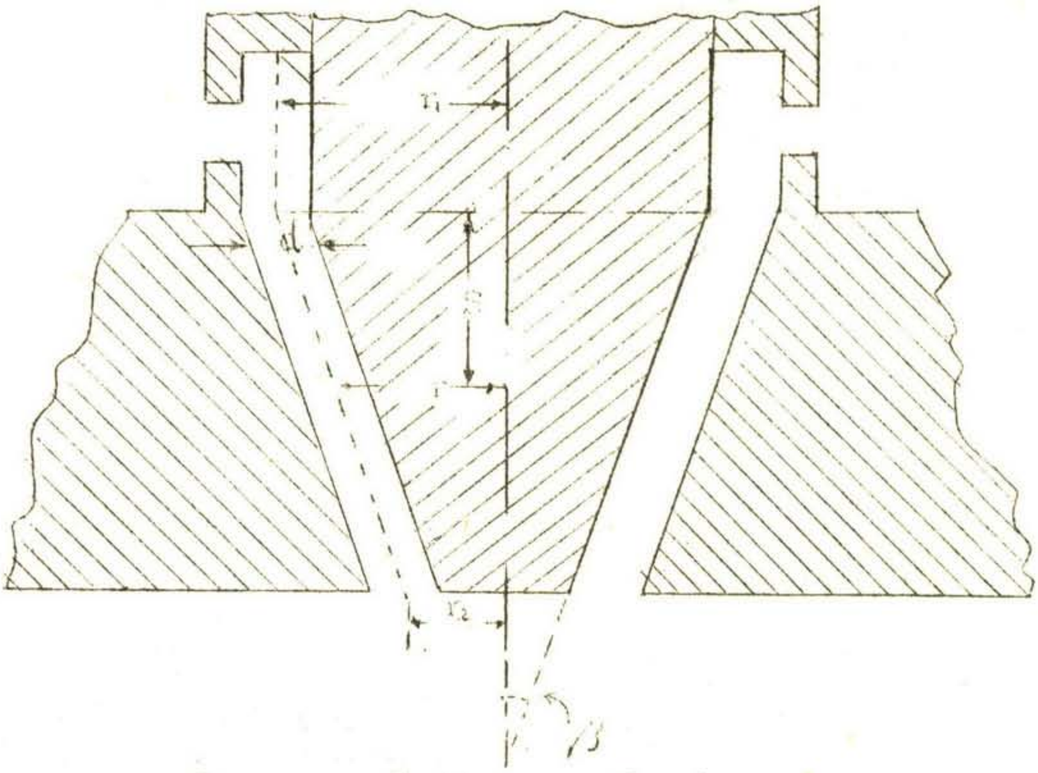


Diagram of Mixing Nozzle.

r	mean radius of inner and outer surface of cone at any point on axis
d	difference of inner and outer radii
s	axial distance measured from base of cone towards orifice
p	pressure drop from feed reservoir to any point in cone
$\beta = \tan^{-1}\left(-\frac{dr}{ds}\right)$	nozzle angle constant
u	speed of rotation at any point
w	linear speed along cone axis at any point
$\alpha = \tan^{-1}\frac{u_2}{w_2}$	spray angle
ρ	average density of liquids
W	mass rate of flow of liquids

Suffix 1 refers to base of nozzle cone

Suffix 2 refers to orifice of nozzle cone

The three following equations are known:

$$(u^2 - w^2)\,\rho/2g = p \tag{1}$$

$$ur = \text{constant} \tag{2}$$

$$w\,2\pi r\,d\,.\,\rho = W \tag{3}$$

and also

$$\tan\alpha = \frac{u_2}{w_2} = \frac{u}{w} \tag{4}$$

3.1 Centrifugal Acceleration

The centrifugal acceleration a_c is given by:

$$a_c = \frac{u^2}{r}$$

utilizing equations (1) and (4) we can write

$$u^2 = \frac{2g}{\rho} p \sin^2\alpha$$

also from equations (3) and (4) it follows that

$$\frac{1}{r} = \frac{2\pi d}{W} \sqrt{2g\rho}\, \sqrt{p}\, \cos\alpha \qquad (5)$$

whence

$$a_c = \sqrt{32}\, \pi \frac{d}{W} \sqrt{\frac{g^3 p^3}{\rho}}\, \sin^2\alpha\, \cos\alpha \qquad (6)$$

Plotting a_c against α, a maximum is found to occur at $\alpha = 54^\circ\ 30'$ as shown in fig. 16.

3.2 Total Acceleration

The total acceleration a is given by

$$a = \sqrt{\left(\frac{dw}{dt}\right)^2 + \left(\frac{du}{dt}\right)^2 + a_c^2}$$

now

$$\frac{dw}{dt} = \frac{dw}{dr} \cdot \frac{dr}{ds} \cdot w$$

$$= -\frac{W^2}{4\pi^2 d^2 \rho^2} \frac{dr}{ds} \frac{1}{r^3}$$

whence from equations (5) and (6)

$$a = \sqrt{32}\, \frac{\pi d}{W} \sqrt{\frac{g^3 p^3}{\rho}}\, \cos\alpha\, \sqrt{\tan^2\beta \cos^2\alpha + \sin^4\alpha} \qquad (7)$$

If a is plotted against α, a maximum is obtained only if

$$\left(\frac{dr}{ds}\right)^2 \leq 2 - \sqrt{3}$$

3.3 Time Integral of centrifugal Acceleration

The time integral of centrifugal acceleration is given by:

$$\int_{t_1}^{t_2} |a_c|\, dt$$

now $$a_c \, dt = a_c \frac{dt}{ds} \frac{ds}{dr} \frac{dr}{dp} \, dp$$

and $$\frac{dt}{ds} = \sqrt{\frac{\rho}{2\,gp}} \, \frac{1}{\cos\alpha}$$

whence $$\int_{t_1}^{t_2} |a_c| \, dt = \cot\beta \sqrt{\frac{2g}{\rho}} \left(\sqrt{p_2} - \sqrt{p_1}\right) \sin\alpha \, \tan\alpha \qquad (8)$$

3.4 Time Integral of Total Acceleration

The time integral of total acceleration is given by

$$\int_{t_1}^{t_2} |a| \, dt = \sqrt{\frac{2g}{\rho}} \left(\sqrt{p_2} - \sqrt{p_1}\right) \sqrt{\cot^2\beta \sin^2\alpha \tan^2\alpha + 1} \qquad (9)$$

4 Results

Taking $$K_1 = \sqrt{32} \, \pi \frac{d}{W} \sqrt{g^3 \, p^3/\rho}$$

and $$K_2 = \sqrt{\frac{2g}{\rho}} \left(\sqrt{p_2} - \sqrt{p_1}\right)$$

the dependence of the four quantities a_c, a, $\int_{t_1}^{t_2} |a_c| \, dt$ and $\int_{t_1}^{t_2} |a| \, dt$

on α and β is given by the four following equations:

$$a_c = K_1 \sin^2\alpha \cos\alpha \qquad (6)$$

$$a = K_1 \sqrt{\tan^2\beta \cos^2\alpha + \sin^4\alpha} \cos\alpha \qquad (7)$$

$$\int_{t_1}^{t_2} |a_c| \, dt = K_2 \cot\beta \sin\alpha \tan\alpha \qquad (8)$$

$$\int_{t_1}^{t_2} |a| \, dt = K_2 \sqrt{\cot^2\beta \sin^2\alpha \tan^2\alpha + 1} \qquad (9)$$

The values of $\frac{a_c}{K_1}$, $\frac{a}{K_1}$, $\frac{\int |a_c| dt}{K_2}$, and $\frac{\int |a| \, dt}{K_2}$ are plotted against α for $\beta = 15^\circ$, 30° and 60° in fig. 16. The curves differ so much that it should be possible to determine experimentally which of the four quantities is the most important in the design of a mixing nozzle.

FIG. 1.

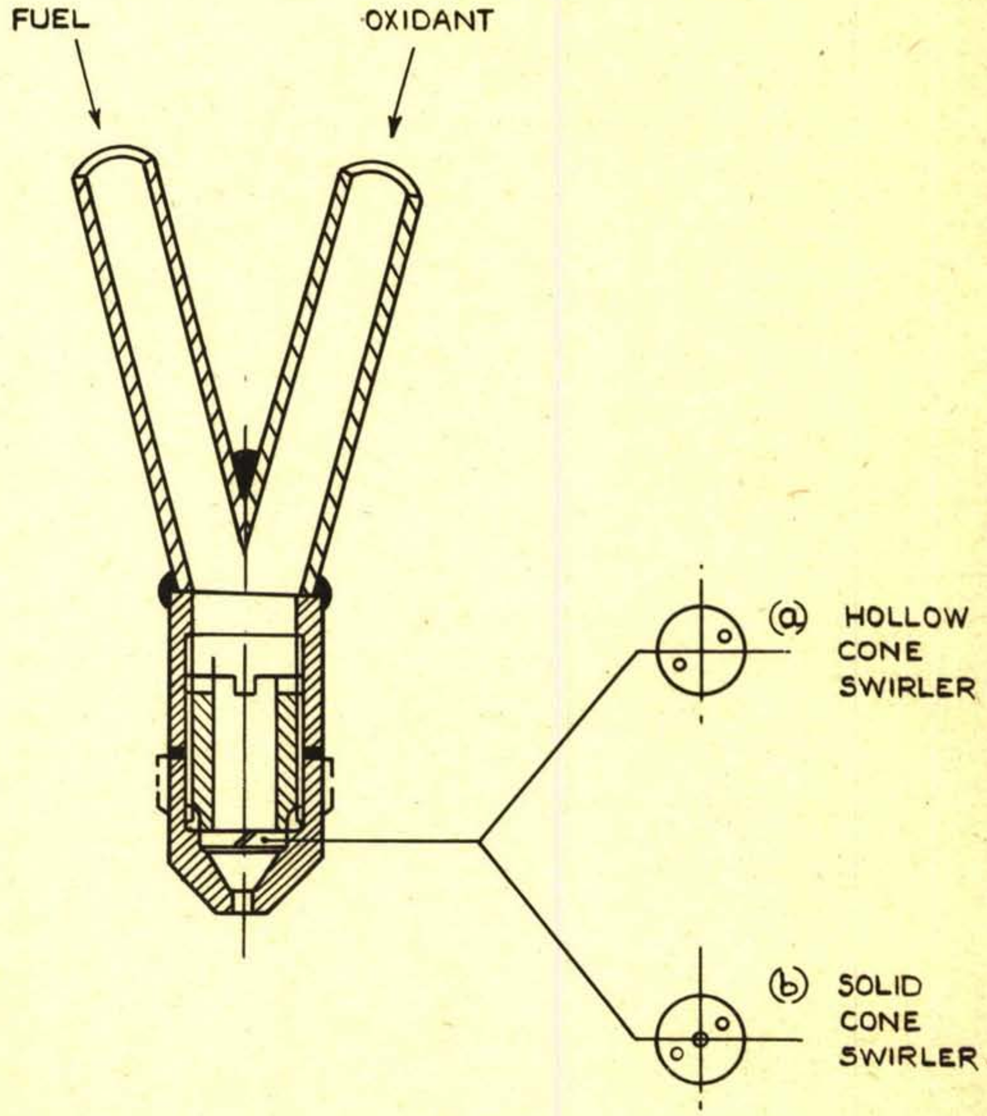
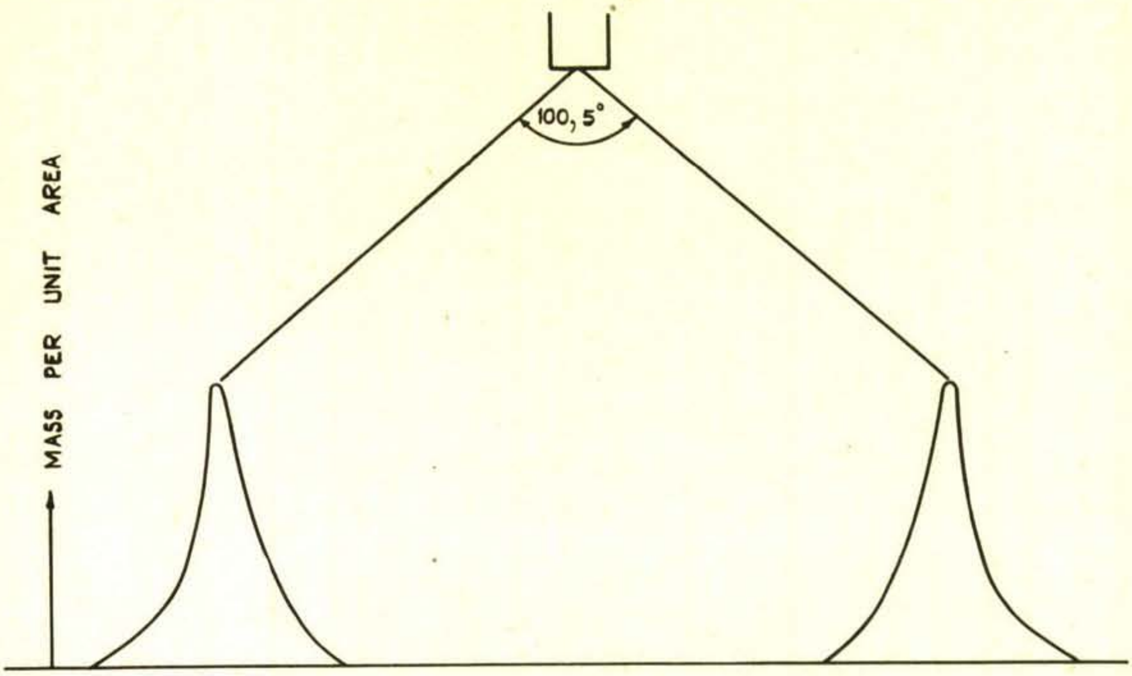
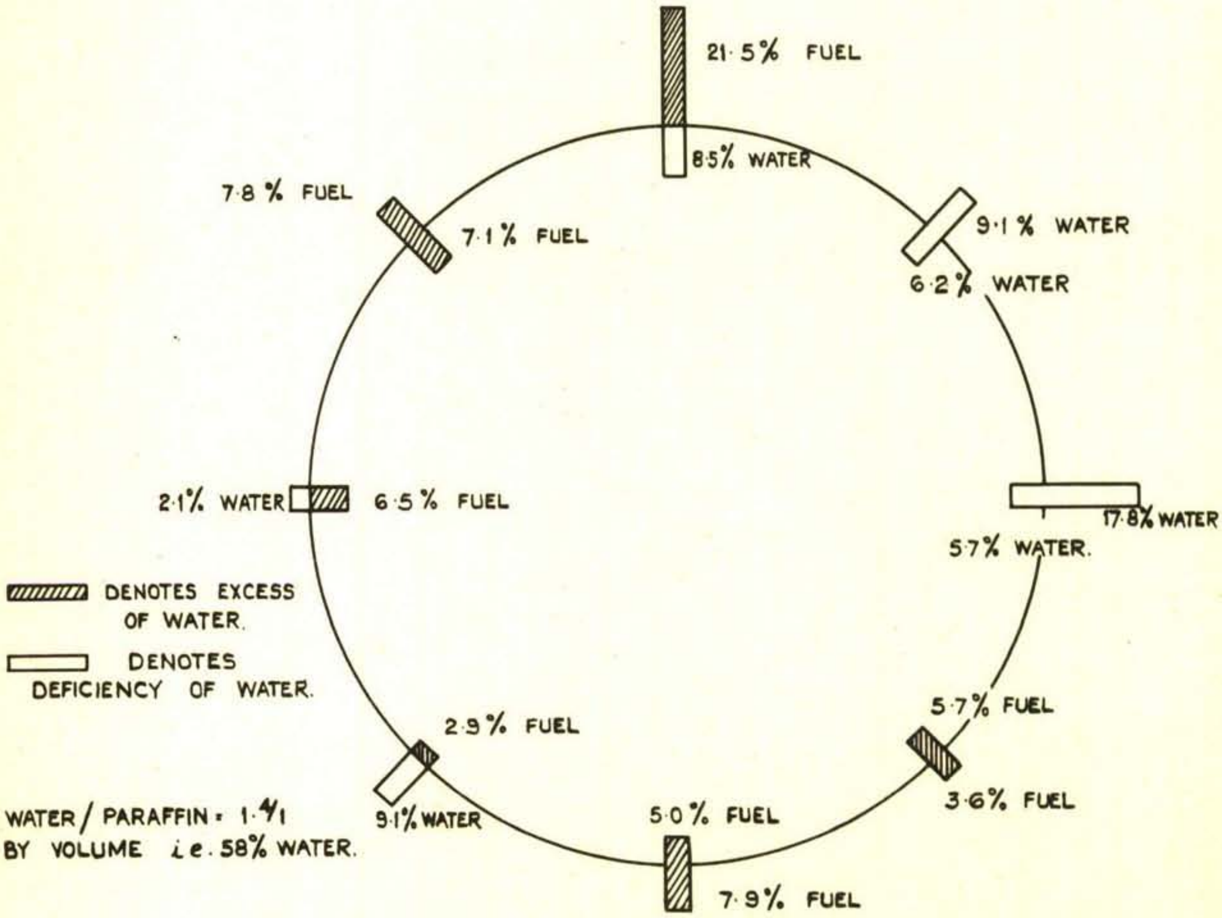


FIG. 1. SECTION THROUGH SIMPLE SWIRL MIXING NOZZLE.



CROSS SECTION MASS DISTRIBUTION.



MIXTURE RATIO VARIATION.

FIG. 2. EMULSION FROM SIMPLE SWIRL NOZZLE.

FIG.3a. FINE EMULSION, x 80

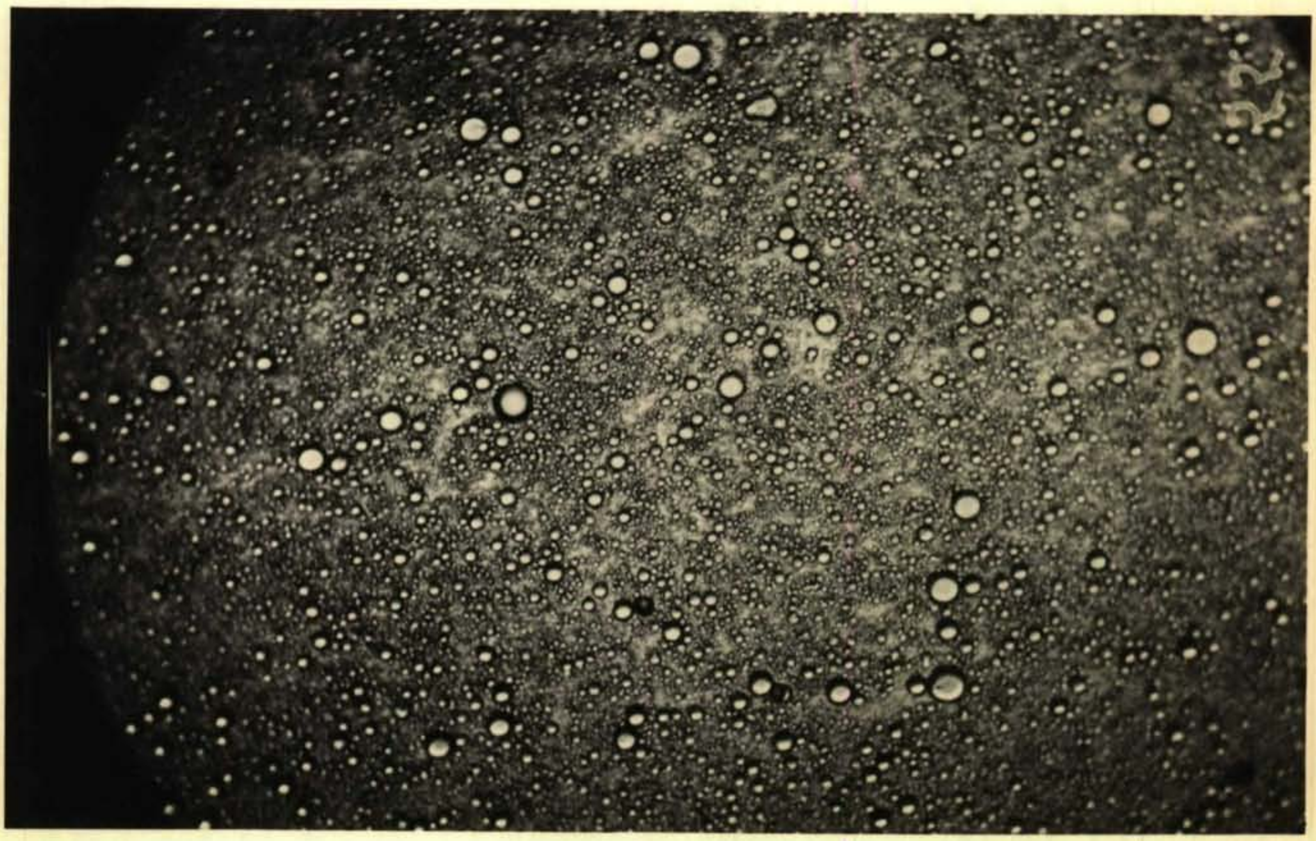
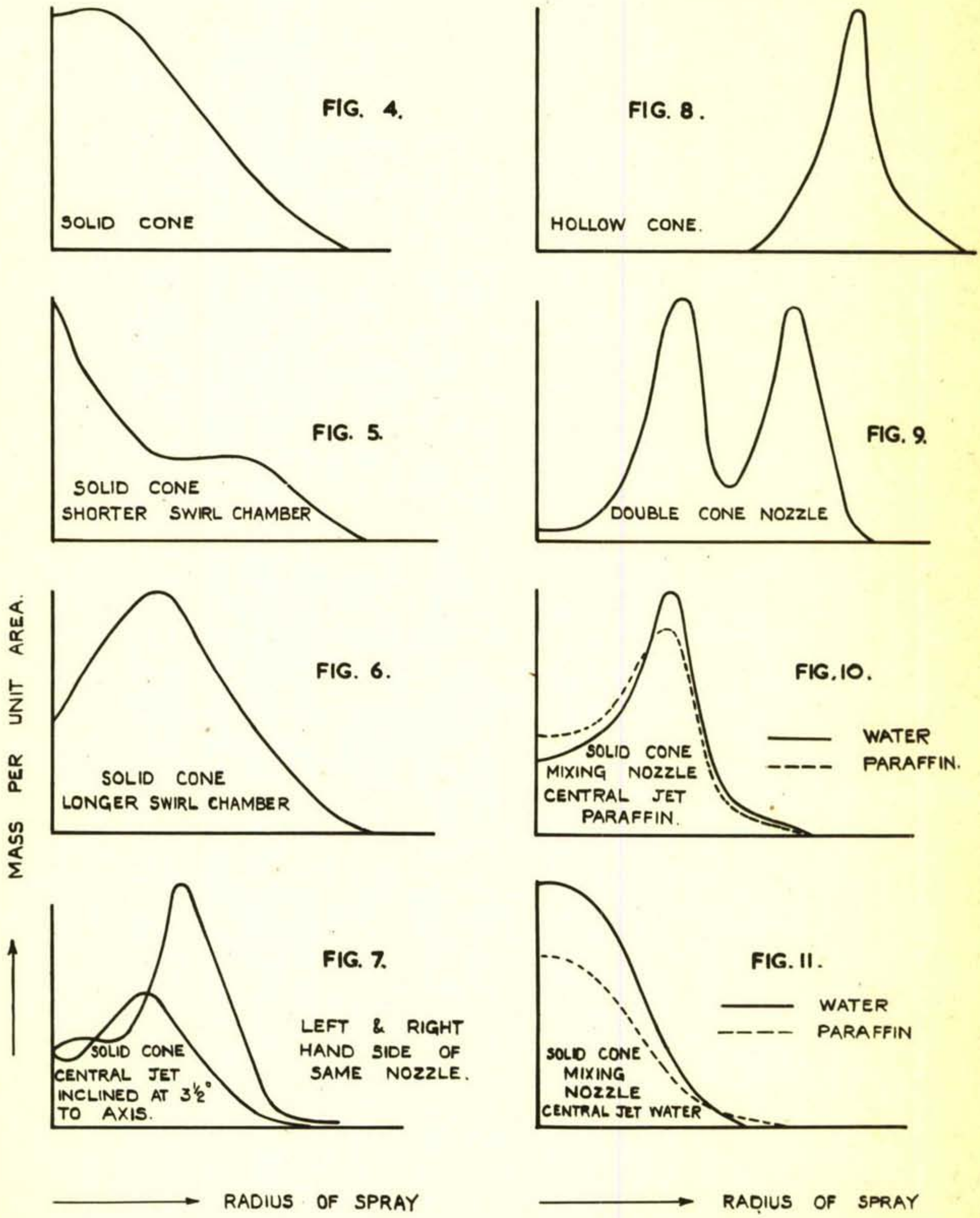


FIG.3b. COURSE EMULSION, x 80

FIG. 4 - 11.



AT A DISTANCE OF 55 mm FROM THE NOZZLE.

FIG. 4-11 MASS DISTRIBUTION OF SPRAY FROM VARIOUS NOZZLES.

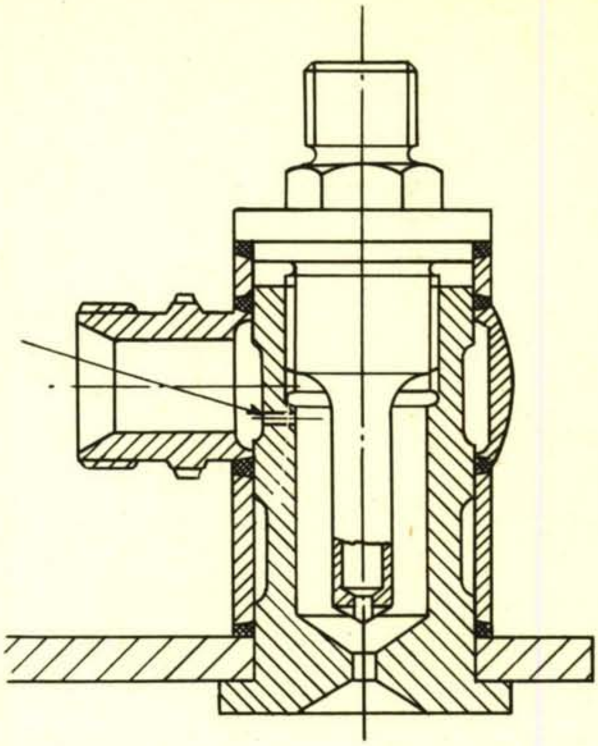


FIG. 12 SOLID CONE MIXING NOZZLE.

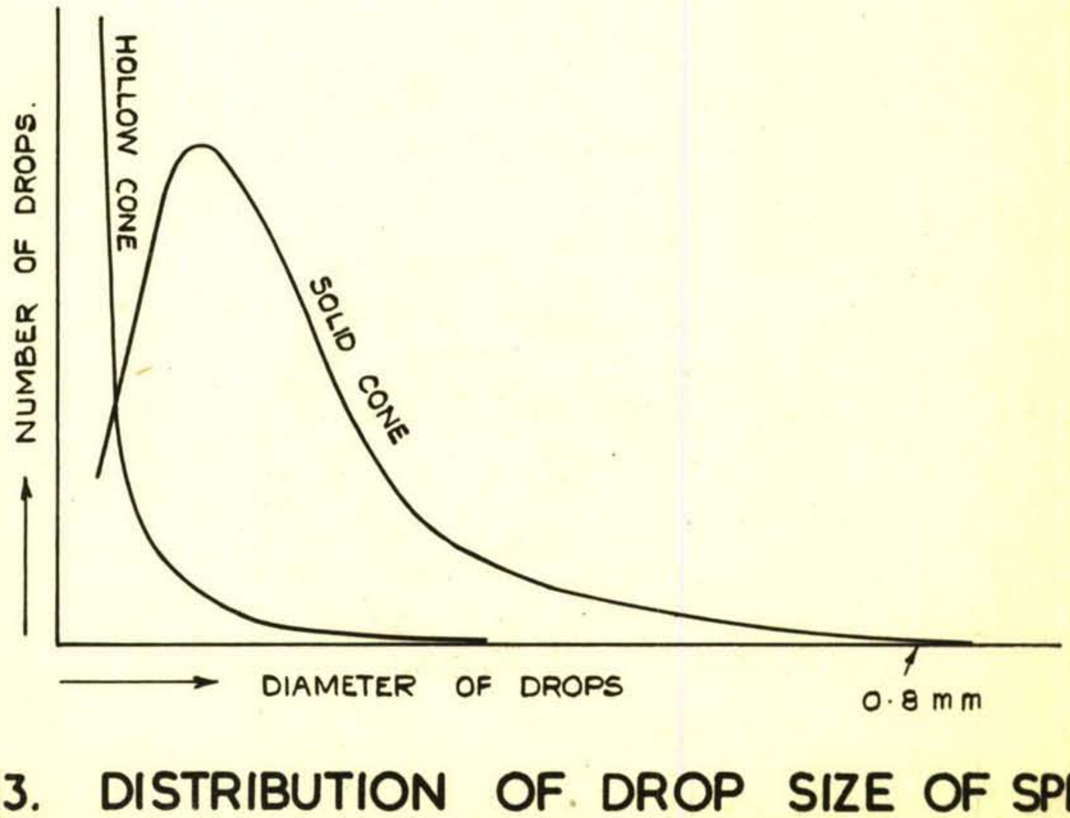
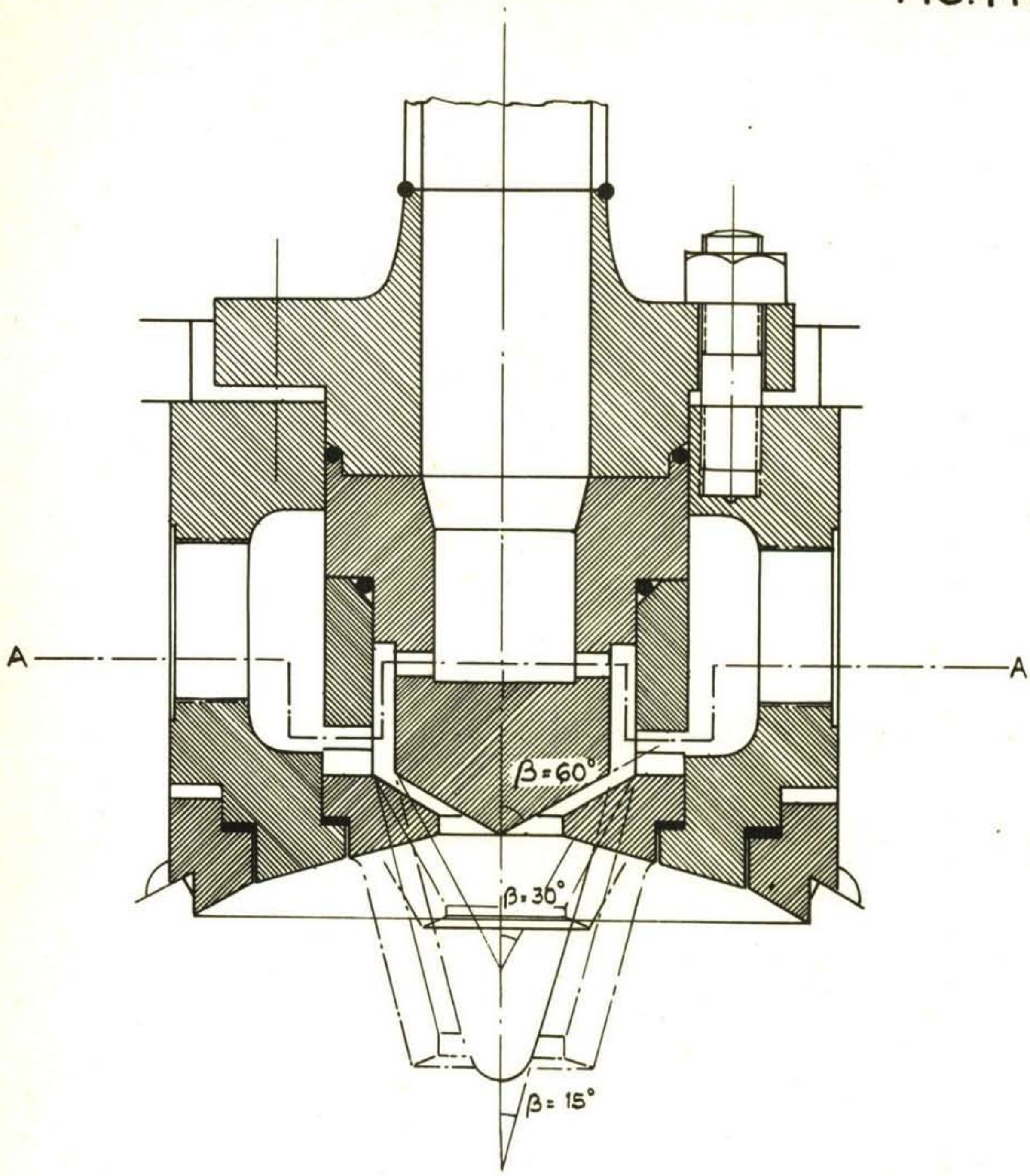


FIG. 13. DISTRIBUTION OF DROP SIZE OF SPRAY FROM HOLLOW AND SOLID CONE NOZZLES.



ARRANGEMENT OF INLET HOLES
(SECTION A - A)

FIG. 14. JET ASSEMBLY OF NEW MIXING NOZZLE. (TYPE B).

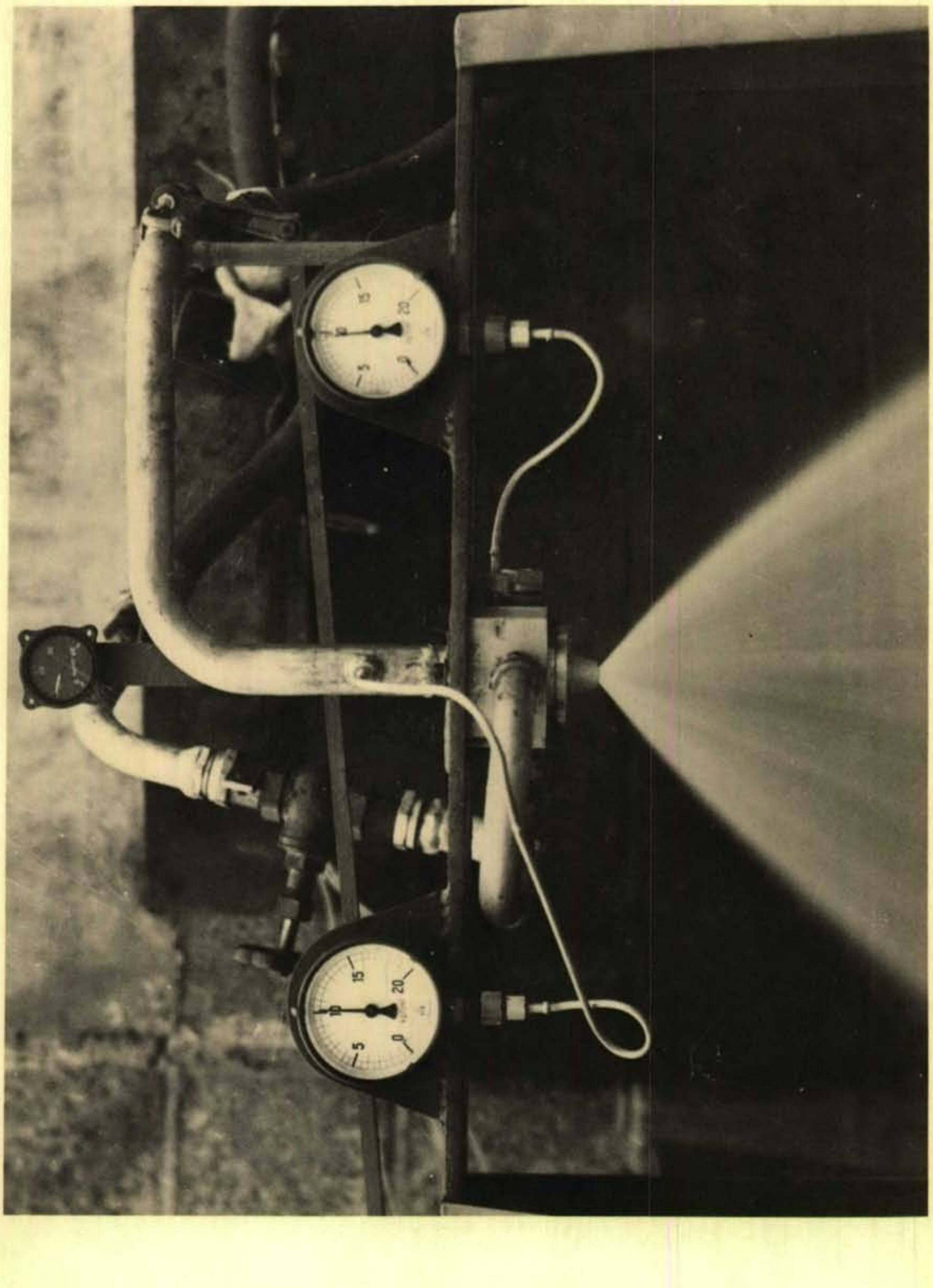


FIG.15. MIXING NOZZLE A (β = 15) IN OPERATION

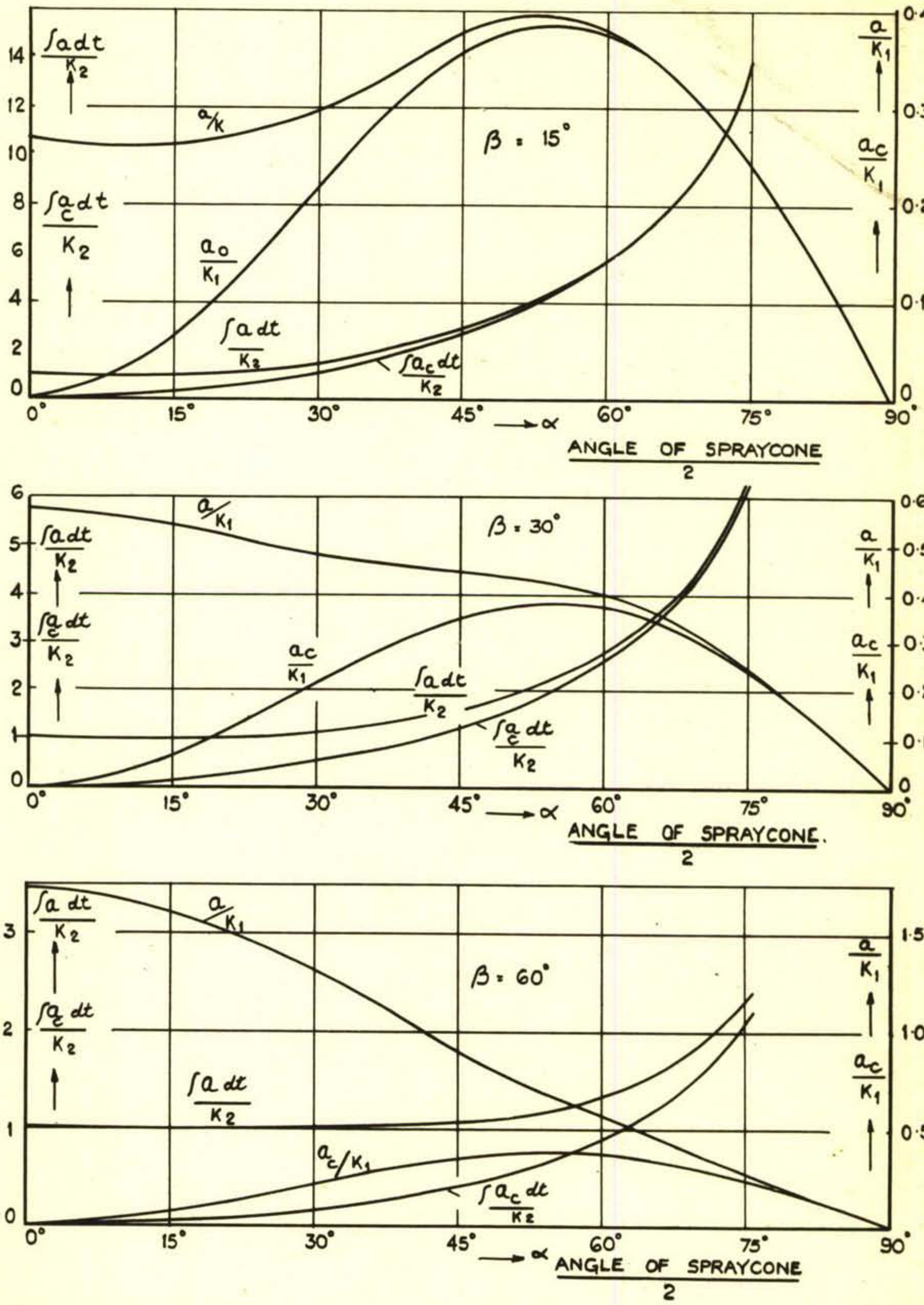


FIG. 16. VARIATION OF CENTRIFUGAL AND TOTAL ACCELERATIONS AND OF CENTRIFUGAL AND TOTAL VELOCITIES FOR DIFFERENT NOZZLE AND SPRAY CONE ANGLES.